

Status Report

**CALIBRATION PARAMETERS FOR  
RESISTIVITY LOGS -- PRELIMINARY FINDINGS**

Project BE8, Task 1, Milestone 4

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## SUMMARY

The principal objective of Project BE8, Residual Oil Saturation Measurement and Estimation Improvement, is to improve the accuracy of resistivity log measurements by developing calibration parameters for Archie's equation, or similar interpretation techniques, as functions of reservoir rock type and reservoir conditions. Preliminary results, obtained in FY86, indicated that temperature and pressure on sandstone rock significantly affected resistivity measurements. Work performed during the first quarter of FY87 confirms and supplements the preliminary results. This report presents electrical resistivity measurements and complete analysis of these measurements on three Berea and three Shannon outcrop core samples. For each core studied, electrical resistivity was measured at three or more temperatures, three water saturations, and more than five net confining pressures and one salinity (2 percent NaCl).

Analysis of the results shows that the cementation factor for the studied cores varied with net confining pressure and temperature. The increase of cementation factor with an increase of confining pressure is believed to result from a loss of brine within the porous medium and a disturbance of the conducting path of brine. Scarcely any temperature effect on the cementation factor of Berea cores was observed; however, the cementation factor decreased with an increase in temperature for Shannon cores because of their clay content.

The saturation exponent was found to vary with temperature, pressure, and brine saturation for all cores tested. When the confining pressure increases, the saturation exponent value decreases at a low brine saturation and increases at a high brine saturation. As the temperature increases, the saturation exponent decreases.

Finally, increasing pore pressure for the only Berea core tested showed the same effects on cementation factor and saturation exponent as those described previously; therefore, it appears that internal pore pressure has almost no effect on cementation factor and saturation exponent.

### METHODOLOGY

The electrical resistance of fully and partially brine-saturated Berea and Shannon outcrop cores was measured at different temperatures and net confining pressures in the laboratory. Three cores for each rock type were analyzed. Core plugs were 1 in. in diameter and 1-3/4 in. in length. The equipment used and the operating procedure followed during these measurements have been previously reported.<sup>1</sup>

Temperatures were varied from 75° to 150° F. Net confining pressures were varied from 500 to 6,000 psi for Berea cores and from 500 to 5,000 psi for Shannon cores. Internal pore pressure was maintained at 0 psig during most of the experiments. For one Berea core, the internal pore pressure was changed from 0 to 5,000 psig in increments of 500 psig. The fluids used were Soltrol-220 and brine at a concentration of 2 percent NaCl for all cores, except for one of the Berea cores in which 10 percent NaCl concentration was used. Brine saturations attained ranged from 36 to 100 percent. Brine saturations were determined by use of the x-ray absorption technique.<sup>2</sup>

Cementation factor ( $m$ ) and saturation exponent ( $n$ ) for each rock type were determined by use of the formation factor ( $F$ ) and resistivity index ( $I$ ) equations (equations 1 and 2)<sup>3</sup> for different temperatures and net confining pressures.

$$F = \frac{R_o}{R_w} = C \phi^{-m} \quad (1)$$

$$I = \frac{R_t}{R_o} = C' S_w^{-n} \quad (2)$$

$C$  and  $C'$  were assumed to be equal to 1 in these preliminary calculations.  $S_w$  and  $\phi$  are water saturation and porosity, respectively. The resistivity ( $R$ ) was computed from the measured electrical resistance.  $R_w$ ,  $R_o$  and  $R_t$  are the water, the rock 100 percent water-saturated, and the rock partially water-saturated resistivities, respectively.

For each temperature, resistance values versus net confining pressure points were obtained on an increasing net confining pressure path. Three temperatures (75°, 110° and 150° F) were investigated with all of the cores, except for one Shannon core for which six temperatures were investigated (75°, 110°, 130°, 150°, 170° and 200° F). Resistance equilibrium (less than  $\pm 0.5$  percent variation in resistance) was obtained at a given temperature within 1 hour and at a given net confining pressure within 5 to 10 minutes. The resistance values of the brines (2 and 10 percent NaCl) at the different temperatures studied were determined from Schlumberger Log Interpretation Charts.<sup>2</sup>

The results presented in the next two sections are at 0 psig internal pore pressure. The last section of this report briefly summarizes the results obtained with a Berea core at different internal aqueous phase pressures.

#### EFFECT OF NET CONFINING PRESSURE AND TEMPERATURE ON CEMENTATION FACTOR

We obtained the results discussed in this section by assuming that equation 1 (Archie's equation) can be applied to all calculated resistivity measurements. Cementation factors were computed using equation 1 assuming  $C$  is equal to 1.

The results from the six cores studied during this work show that the cementation factor varies with net confining pressure and temperature. For the Berea cores, a 3 to 5 percent increase in  $m$  values was observed for the three temperatures studied when net confining pressure was increased from 500 to 6,000 psi. The pressure effect on  $m$  observed for Shannon cores was slightly more significant (5 to 8 percent increase) when net confining pressure was increased from 500 to 5,000 psi. The increase of  $m$  value with the increase of net confining pressure is believed to be caused by the loss of conducting fluid (brine) within the porous medium.

The porosity changes of the studied cores were monitored as net confining pressure increased. The  $m$  values at 75° F were recalculated for the four cores studied using the new porosity which has resulted from changes in pressure. Through this recalculation, a constant value of  $m$  was obtained for one of the Berea cores, indicating that the pressure effect on  $m$  can be interpreted completely by the reduction of porosity due to pressure. For the other cores studied, the pressure effect of  $m$  values could not completely be accounted for through porosity changes. These results suggest a disturbance of the conducting path of brine or a redistribution of brine within the tested cores.

The results show almost no temperature effect on  $m$  values in Berea cores. (Fig. 1); however,  $m$  values decrease with an increase in temperature for the Shannon cores. As the temperature increases, the effect of temperature on  $m$  is reduced (Fig. 2). Similar results were reported by Waxman and Thomas.<sup>5</sup>

The temperature effect on  $m$  in Shannon cores does not appear to be a function of net confining pressure (a 1 to 5 percent decrease in  $m$  with increasing temperature is observed at either 500 or 5,000 psi). The reason for this large effect of temperature on Shannon cores is the high conductivity associated with the high clay content. Berea cores have less clay content -- cation exchange capacity (CEC) less than or equal to 0.3 milliequivalent per kilogram of rock -- than the Shannon cores (CEC about 4.2 milliequivalent per kilogram of rock). Waxman and Thomas explained the increase in shaly sand conductivity with increasing temperature to be accounted for by the equivalent ionic conductivity of the counter ions associated with the clay, in addition to the equilibrating brine resistivity.

Conduction by clay-exchange cations is a more complex process than conduction by solution ions. The clay-exchange cations migrate in the electric field from one exchange site to another on the surface of clay plates and through the equilibrating electrolyte. The increase of temperature will increase the migration of clay-exchange cations to contribute to an additional "clay conductivity."

The temperature dependence of the specific rates of most chemical reactions including ionic mobility is commonly described by Arrhenius activation energies. The activation energy ( $E_e$ ) associated with the maximum ion-exchange cation mobility ( $\lambda$ ,  $\text{Na}^+$  in this study) can be expressed in the form of the Arrhenius equation as:

$$\lambda_{Na^+} = Ae^{-E_e/RT} \quad (3)$$

The activation energies of  $Na^+$  in relation 3 at a temperature range of 72° to 392° F were reported by Waxman and Thomas.<sup>5</sup>  $E_e$  of  $Na^+$  decreases from 5,600 cal/mol at 72° F to 1,450 cal/mol at 392° C. This decrease of  $E_e$  with temperature for clay cations accelerates the diminish of temperature effect in relation 3. At a high temperature level (302° to 392° F), an increasing diffuse double layer at the clay/water surface decreases the value of activation energy of the clay cation to the activation energy value of ion in the solution (1,450 cal/mol). Therefore, at high temperature, relation 3 explains that the temperature effect is diminished at higher temperature for shaly sands as was observed in this study for Shannon rocks.

#### EFFECT OF NET CONFINING PRESSURE AND TEMPERATURE ON SATURATION EXPONENT

The saturation exponent was calculated using equation 2 assuming  $C'$  to be 1. The  $n$  values were found to vary with temperature, pressure, and brine saturation. All of the electrical resistance measurements were conducted at a pore pressure of 0 psig (open system).

In general, the results indicate that  $n$  value increases with pressure at high brine saturation, is constant with respect to confining pressure at intermediate brine saturation values, and decreases with an increase in pressure at low brine saturation. Note that for the behavior described above, an intermediate brine saturation for a given rock type may correspond to a low saturation for another rock type. As an example, for a Berea rock (rock B2),  $n$  increases with an increase in pressure for 70 percent brine saturation (Fig.

3), whereas for a Shannon rock (rock S2),  $n$  decreases with an increase in pressure for 78 percent brine saturation (Fig. 4). This behavior is not yet completely understood, but it appears to be primarily caused by the difference in redistribution of the fluids in the tested cores when net confining pressure is increased.

The decrease in rock resistivity with an increase of pressure at a low brine saturation and the increase in rock resistivity with an increase in net confining pressure at high brine saturation may be explained as follows. Rock resistivity is a measure of the ionic conductivity in the aqueous phase. Variation in rock resistivity as a function of pressure or temperature reflects a change of ionic mobility and/or the length of diffusion path for conducting ions. The ionic mobility remains the same at a constant temperature; therefore, a change in length of the conducting path under an increase in net confining pressure is responsible for the accompanying change in rock resistivity. For a fully or highly brine saturated rock, when the net confining pressure increases the conducting path of ions (by increasing the number and extent of grain contacts) inside the core, the rock resistivity increases, which, in turn, increases the  $n$  value. For a rock at low or irreducible water saturation, the change of pore fluid distribution with net confining pressure may improve the continuity of the aqueous phase within the rock which results in a decrease in resistivity.

For almost all of the Berea cores, a decrease in  $n$  value is observed at constant brine saturation when the temperature is increased from 75° to 150° F. The temperature effect on  $n$  appears to be more significant at 500 psi (4 to 13 percent decrease) than at 5,000 psi (2 to 8 percent decrease). At low water saturations, the temperature effect on  $n$  values appears more significant for the low temperature range (75° to 110° F) than the high temperature range



(110° to 150° F).

Different temperature effects on  $n$  were observed for all of the Shannon cores. As in the Berea cores, a decrease in  $n$  value was observed at constant brine saturation when the temperature increased from 75° to 150° F. However, the temperature effect on  $n$  does not appear to be a function of net confining pressure. In addition, the temperature effect on  $n$  is not a function of temperature range.

The observed decrease in  $n$  value when temperature increases may be due to changes in core wettability and/or interfacial forces which results in a decrease of resistivity. The work in FY88 will include measurements of these properties at different temperatures, so that the phenomenon may be better understood.

Only two of the cores tested (one Shannon core, S1, and one Berea, B1) showed a decrease in  $n$  value when the temperature changed from 75° F to 110° F followed by an increase in  $n$  value when the temperature changed from 110° F to 150° F. This behavior will be verified in future experiments.

#### EFFECT OF INTERNAL PORE PRESSURE ON CEMENTATION FACTOR AND SATURATION EXPONENT

A set of rock resistivity data was measured for one of the Berea cores, B1, at different internal pore pressures (0, 1,000, 2,000, 3,000, 4,000 and 5,000 psig). The corresponding confining pressure varied from 500 to 6,000 psig. Temperatures and brine saturations varied from 75° to 150° F and 36 to 76 percent, respectively. The results show no variation in the cementation factor with internal pore pressure. A maximum of 1 percent deviation was found in  $m$  at net confining pressures of 500 and 1,000 psi when the internal pore pressure was varied from 0 to 5,000 psig. This deviation is within

experimental error. Based on results obtained so far, it can be concluded that internal pore pressure has no effect on cementation factor for the Berea core tested. The same effect of net confining pressure and temperature on cementation factor as reported previously was observed at the different internal pore pressures studied.

Internal pore pressure, however, was observed to have some slight effect on the saturation exponent. A maximum of 5 percent deviation was found in  $n$  at net confining pressures of 500 and 1,000 psi when the internal pore pressure was varied from 0 to 5,000 psig. This deviation does not follow any trend with internal pore pressure, temperature, and brine saturation.

At different internal pore pressures, the same effect of net confining pressure and temperature on  $m$  and  $n$ , as described in the previous sections of this report, was observed.

### CONCLUSIONS AND RECOMMENDATIONS

1. The values of both the cementation factor and the saturation exponent vary with net confining pressure and temperature. This phenomenon indicates the importance of taking into account the effect of reservoir pressure and temperature when calibrating resistivity logs for interpretation of water saturation.

2. The pressure effect on cementation factor and saturation exponent may be a result of the loss of brine within the porous medium and a disturbance of the conducting path of brine.

3. The temperature effect on cementation factor and saturation exponent can be explained from the ionic mobility of brine and clay, using the Arrhenius' equation.

4. A further study of the effect of temperature on rock wettability and

the effect of net confining pressure on the conducting path of brine within the rock is recommended for a better understanding of rock resistivity under reservoir conditions.

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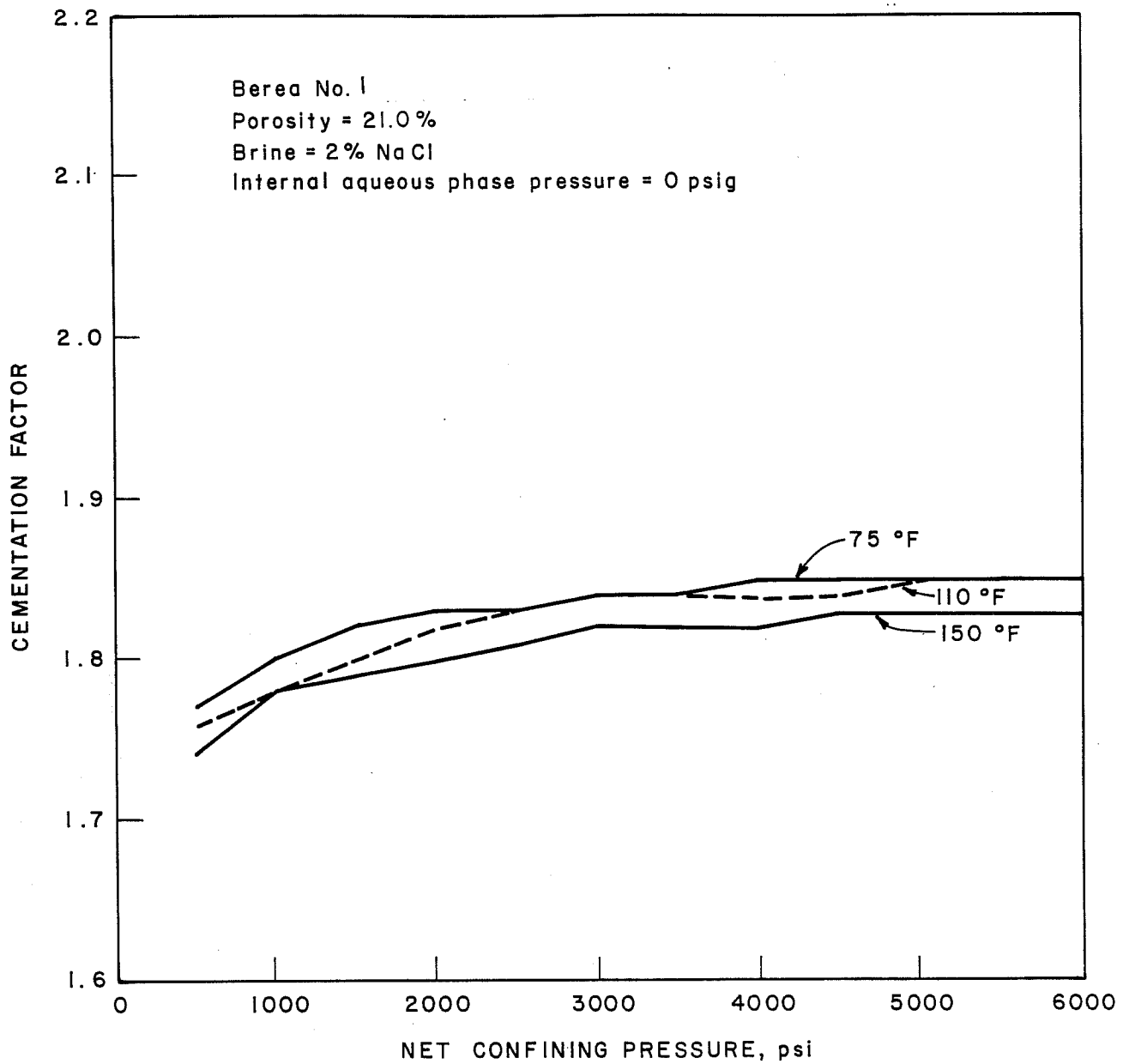


FIGURE 1. - Temperature and pressure dependence of cementation factor in Berea cores.

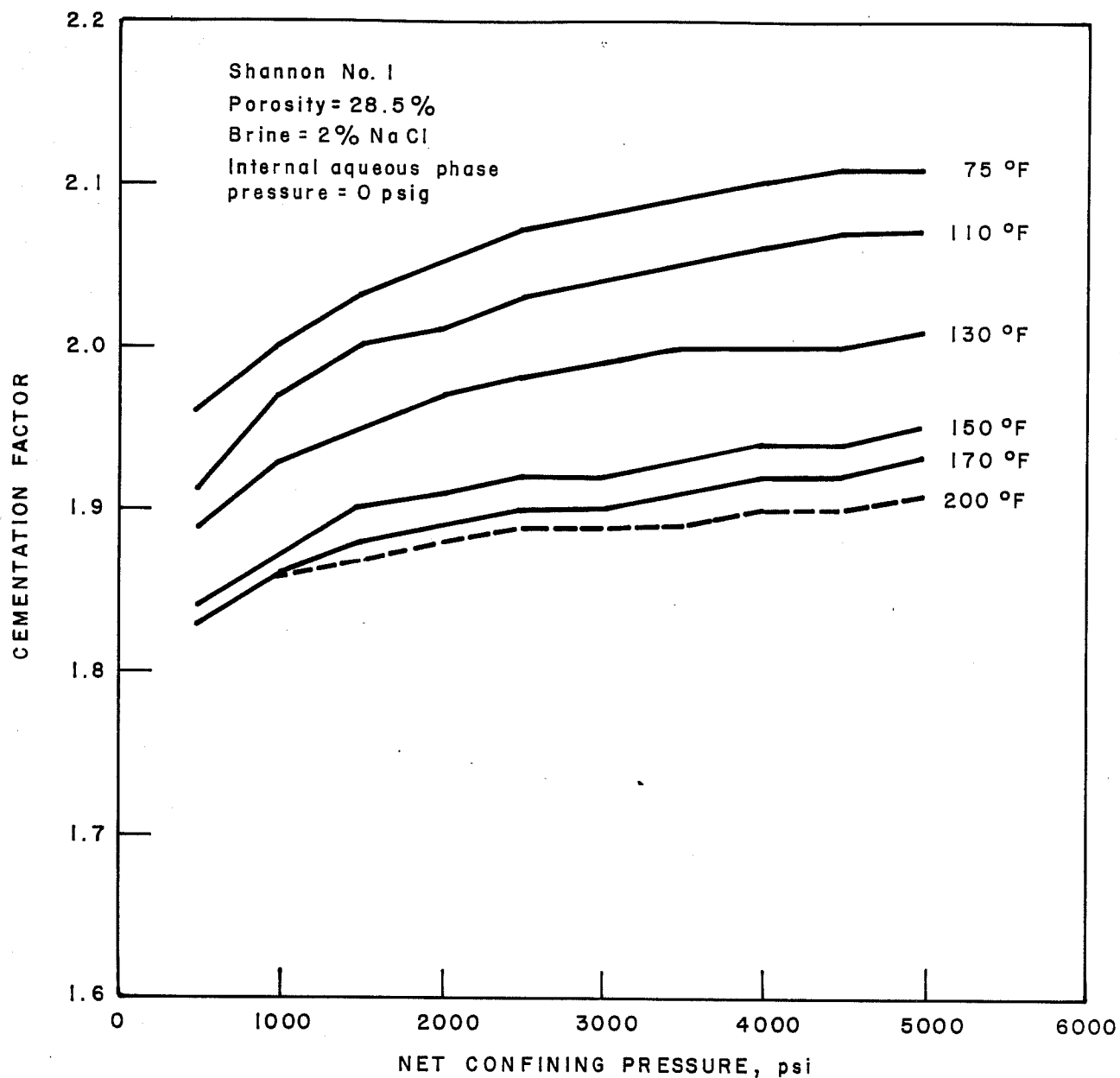


FIGURE 2. - Temperature and pressure dependence of cementation factor in Shannon cores.

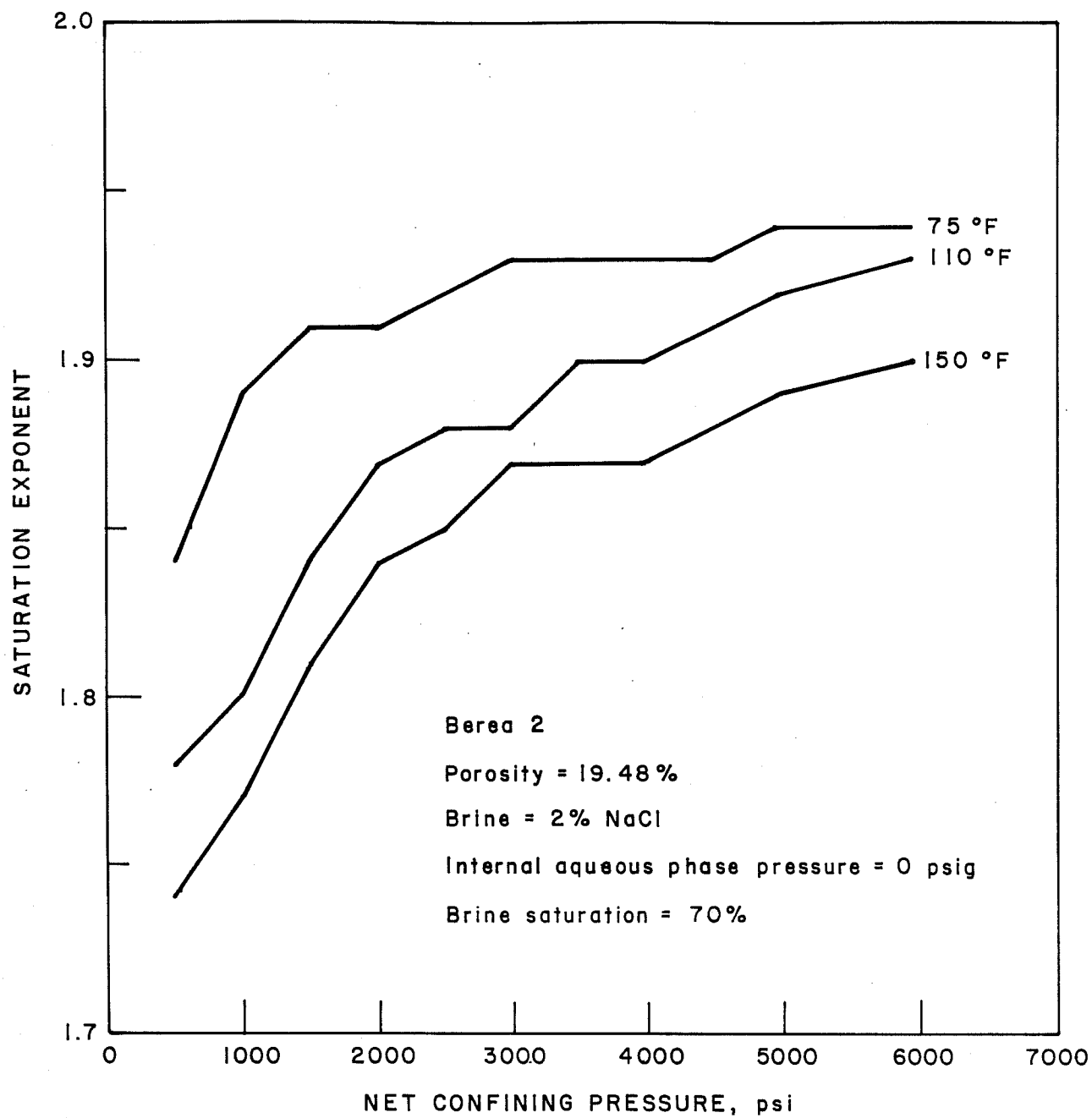


FIGURE 3. - Temperature and pressure dependence of saturation exponent in Berea cores.

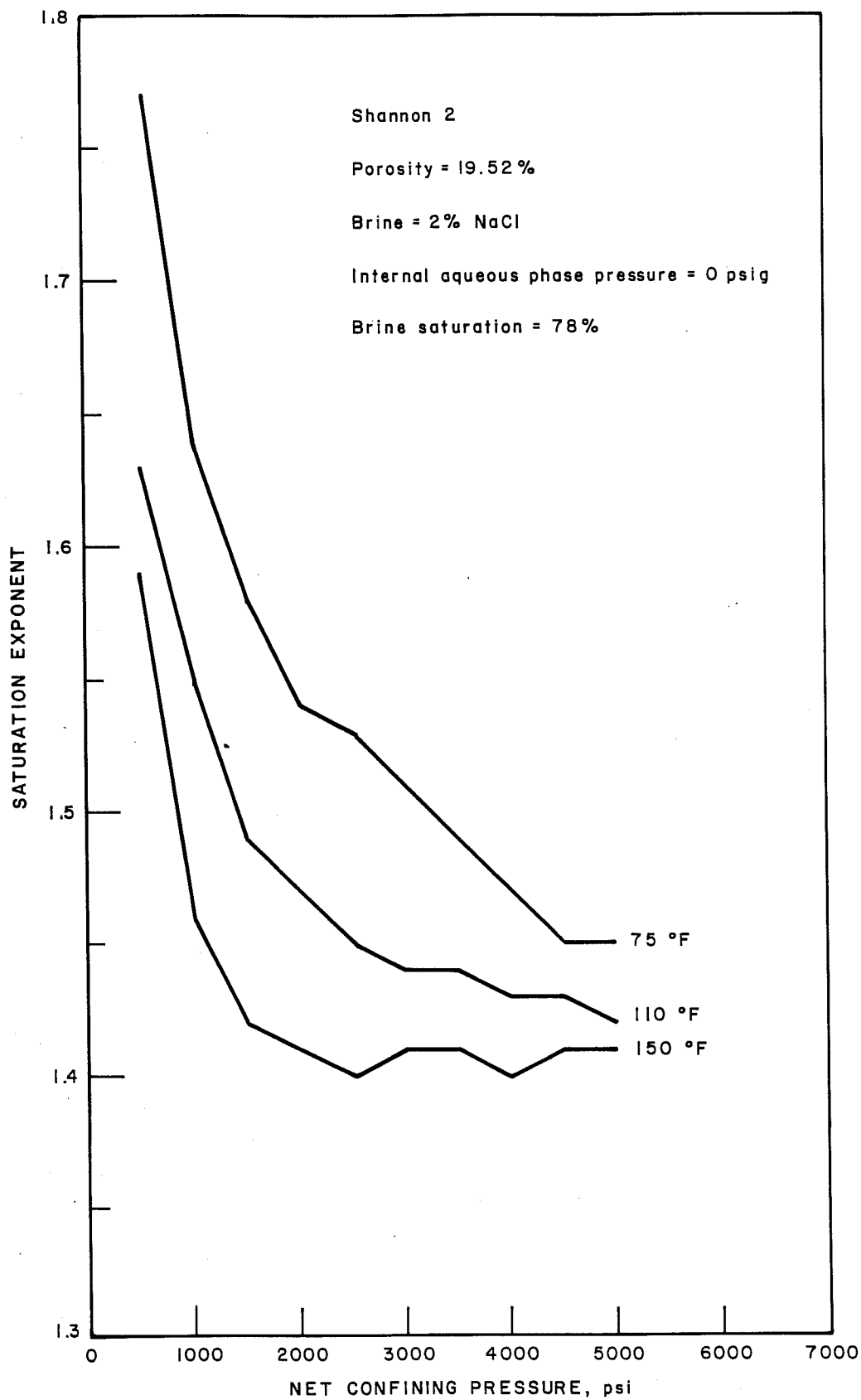


FIGURE 4. - Temperature and pressure dependence of saturation exponent in Shannon cores.